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Effect of Global Warming on the Yields of Strawberry in Queensland: A Mini-Review

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Abstract: Light, temperature and rainfall affect the growth and yield of strawberry plants (*Fragaria* × *ananassa* Duch.). The objective of this review was to determine the impact of global warming on the yields of strawberry in a temperate (summer crop) and subtropical environment (winter crop) in southern Queensland, Australia. Information was collected on the changes in temperature over five decades in two locations in this area. The relationship between relative yield and temperature from published data was used to determine the impact of global warming on productivity in the two locations. Finally, the impact of elevated concentrations of CO_2 and temperature on yield was examined from studies in the literature. The average daily mean temperature has increased by 2 °C over the season on the Sunshine Coast (winter crop) since 1967 ($p < 0.001$, $R^2 = 0.69$). The impact of global warming has been less severe on the Granite Belt (summer crop), with a 1 °C increase in temperature ($p < 0.001$, $R^2 = 0.37$). Information was collected from the literature on the yield in individual temperature regimes in an experiment and these data were compared with the maximum yield in the same experiment (relative yield). There was a negative linear relationship between relative yield and temperature in most of the published literature. The mean (± s.d. or standard deviation) estimate of the slope from the regression was −0.14 (± 0.14), the median was −0.11 and the range was from −0.51 to 0.11 (n = 14 studies). Increases in temperature were associated with a decrease in yield of 14% to 28% in the two areas in Queensland. The results of other research indicated that elevated concentrations of CO_2 do not benefit productivity when combined with elevated temperatures. Further decreases in yield are expected in the next few decades in the absence of heat-tolerant cultivars or other mitigating strategies.

Keywords: climate; CO_2 concentration; global warming; model; net CO_2 assimilation; review; subtropics; temperate; temperature; yield

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1. Introduction

Global production of strawberry (*Fragaria* × *ananassa* Duch.) is about 9 million tonnes each year [1–3]. The crop is important in China and the United States and throughout much of Europe. The plant is adapted to a wide range of environments, with commercial production in areas with a cool or warm temperate climate, a cool or warm subtropical climate or a Mediterranean climate [4–8].

The main scenarios for global climate change include an increase in the concentration of carbon dioxide (CO_2) and an increase in average temperatures. Several studies suggest that yield and fruit quality in strawberry will decrease with climate change [9–22]. Modelling in California demonstrated that productivity will decrease by 10% by 2050 and by 40% by 2099 [14,15]. In these investigations, low yields under climate change were associated with high temperatures and drought.

Strawberry growers in Australia produce 90,000 tonnes of fruit worth AUD 450 million each year. The main production centers are in Queensland (42%), Victoria (36%) and Western Australia (10%). There are smaller industries in South Australia (7%), Tasmania (4%) and New South Wales (1%). Eighty-seven per cent of the supply goes to the retail sector and thirteen per cent to the food service sector. There are two principal growing areas in Queensland, each with a different production season. The bulk of the winter crop is produced from May to October on the Sunshine Coast. The summer crop is produced from October to May at elevation on the Granite Belt.

The objective of this review was to determine the impact of global warming on the yields of strawberry in a temperate (summer crop) and subtropical environment (winter crop) in southern Queensland, Australia. There is no information on the impact of global warming on the yields of strawberry in Queensland or the relationship between yield and temperature under field conditions in this area. Data were collected on the changes in temperature over the past five decades on the Sunshine Coast (winter crop) and the Granite Belt (summer crop). The relationship between yield and temperature from published data was used to assess the impact of global warming on productivity in the two areas. Finally, the impact of elevated concentrations of CO_2 and temperature on yield was examined from studies in the literature.

2. Data Collection

Long-term weather data were collected for Nambour on the Sunshine Coast (latitude 26.6° S, longitude 152.9° E and elevation 29 m) and Applethorpe on the Granite Belt (latitude 28.6° S, longitude 151.9° E and elevation 872 m) (www.bom.gov.au) accessed on 30 October 2022. These data included long-term monthly average daily maximum and minimum temperatures, daily solar radiation and total monthly rainfall. Data were also collected on daily maximum and minimum temperatures from 1967 to 2021. Additional information was collected on the changes in the average temperature for Australia (www.bom.gov.au) and the globe (www.climate.nasa.gov) accessed on 30 October 2022.

The relationship between yield and temperature in strawberry from published data was used to assess the impact of global warming on productivity in the two areas in Queensland. Information was collected from the literature on the yield in an individual temperature regime in an experiment and these data were compared with the maximum yield in the same experiment (relative yield). The relationship between relative yield and temperature in each experiment was analyzed by linear or quadratic regression using GenStat (Version 21; VSN International, Hemel Hempstead, UK).

Additional data were collected from the literature on the yields of strawberry under elevated CO_2 and elevated temperatures.

3. Changes in Temperature

There are differences in climate between the two main strawberry areas in Queensland. It is warmer and wetter at Nambour on the Sunshine Coast than at Applethorpe on the Granite Belt, whereas solar radiation levels are similar. Average yearly maximum temperatures are 26.1 °C and 20.9 °C in the two areas, average minimum temperatures are 15.9 °C and 9.0 °C, total yearly rainfall is 1,698 and 756 mm and average daily solar radiation is 17.9 and 18.4 MJ per m^2, respectively.

The average daily mean temperature from May to October at Nambour has increased from 16.0 °C in 1967 to 18.0 °C in 2021, equivalent to a rise of 0.45 °C per decade (Figure 1; $p < 0.001$, $R^2 = 0.69$). The maximum has increased by 0.17 °C per decade ($p = 0.001$, $R^2 = 0.17$), while the minimum has increased by 0.73 °C per decade ($p < 0.001$, $R^2 = 0.66$).

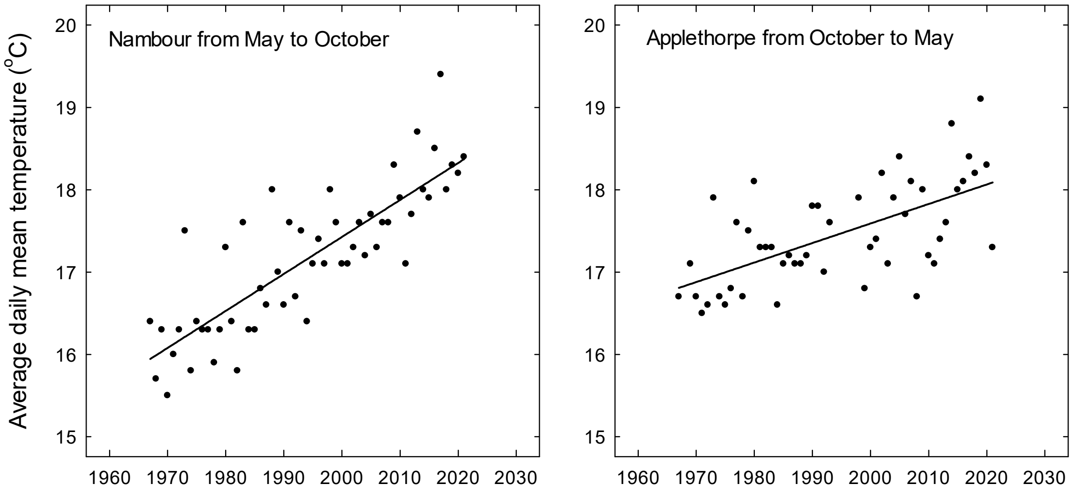

Figure 1. Changes in average daily mean temperature at Nambour from May to October and at Applethorpe from October to May from 1967 to 2021. Data are from www.bom.gov.au. For Nambour: Temperature (°C) = Intercept + 0.0451 × Year ($p < 0.001$, $R^2 = 0.69$). For Applethorpe: Temperature (°C) = Intercept + 0.0236 × Year ($p < 0.001$, $R^2 = 0.37$).

The average daily mean temperature over the season at Applethorpe has increased, but not as much as in Nambour (Figure 1). The mean temperature from October to May has increased from 16.8 °C in 1967 to 17.8 °C in 2021, equivalent to a rise of 0.24 °C per decade ($p < 0.001$, $R^2 = 0.37$). The maximum has increased by 0.38 °C per decade ($p < 0.001$, $R^2 = 0.35$), while the minimum has increased by 0.09 °C per decade ($p = 0.029$, $R^2 = 0.08$).

The average daily mean temperature from January to December at Nambour has increased by 0.34 °C per decade (Figure 2; $p < 0.001$, $R^2 = 0.74$). The mean temperature over the year at Applethorpe has increased by 0.25 °C per decade (Figure 2; $p < 0.001$, $R^2 = 0.47$).

The average daily mean temperature in Australia from January to December has increased by 0.24 °C per decade (Figure 2; $p < 0.001$, $R^2 = 0.53$). The average temperature across the globe has increased by 0.18 °C per decade (Figure 2; $p < 0.001$, $R^2 = 0.91$). The temperature for Nambour has increased at a faster rate than for Australia and the globe. The temperature for Applethorpe has increased at a similar rate as for Australia and at a faster rate than for the globe.

Temperatures across the globe have increased over the past fifty years [23]. The rate of warming varies from one region to the next and there are differences between winter and summer and between days and nights.

Climate change is associated with increases in temperature in southern Queensland. Olesen [24] studied warming in coastal northern New South Wales, Australia and found that winter temperatures had increased by 1.5 °C from 1963 to 2009, whereas summer ones were largely unchanged. Frederiksen and Osbrough [25] showed that the shifts in temperature in Australia had mainly occurred in the past 20 years. Mean and maximum temperatures are projected to increase by 2 °C around mid-century in many areas of the globe [26].

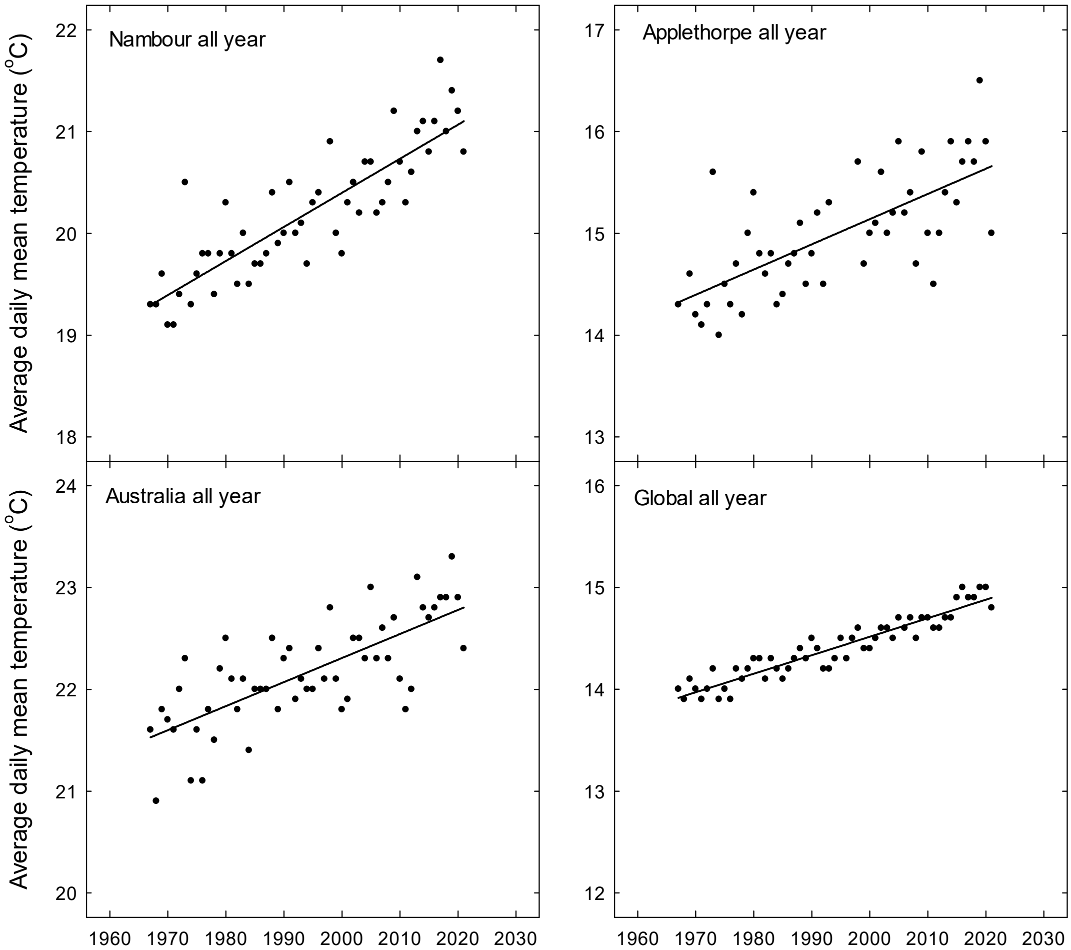

Figure 2. Changes in average daily mean temperature during the year for Nambour, Applethorpe, Australia and the globe from 1967 to 2021. Data are from www.bom.gov.au and www.climate.nasa.gov. For Nambour: Temperature (°C) = Intercept + 0.0339 × Year ($p < 0.001$, $R^2 = 0.74$). For Applethorpe: Temperature (°C) = Intercept + 0.0247 × Year ($p < 0.001$, $R^2 = 0.47$). For Australia: Temperature (°C) = Intercept + 0.0240 × Year ($p < 0.001$, $R^2 = 0.53$). For Globe: Temperature (°C) = Intercept + 0.0184 × Year ($p < 0.001$, $R^2 = 0.91$).

4. Relationship between Yield and Temperature

The relationship between productivity and temperature in strawberry was assessed from published data (Table 1; $n = 26$ studies). There was a negative linear relationship between relative yield (yield in a specific temperature regime/maximum yield in an experiment) and temperature in most of the studies. The mean (± s.d. or standard deviation) estimate of the slope from the regression was −0.14 (± 0.14), the median was −0.11 and the range was from −0.51 to 0.11 (Figure 3; $n = 14$ studies). This means that on average, yield decreased by 14% for each degree increase in temperature. There are no data available on the effect of temperature on the productivity of strawberry in Australia from either glasshouse or field studies.

Information was collected on the effect of temperature on productivity from studies in growth chambers and in the field. There are issues with both types of experiments. Yields and light levels are low in growth chambers and there are limited or inappropriate replication [42]. Temperature is often correlated with solar radiation in the field, making it difficult to separate the importance of the two factors on growth and yield [33].

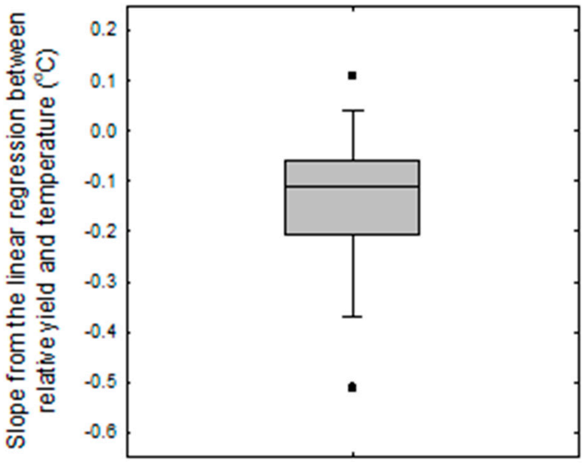

Figure 3. Box plot for the slope from the linear regression between relative yield and average daily mean temperature in strawberry (n = 14 studies). Data are from the citations shown in Table 1.

A few studies were excluded from the analysis. This was because the plants were grown at relatively low temperatures below 17 °C [41] or there was a strong correlation between temperature and solar radiation in the field [33,37]. Le Mière et al. [29] investigated the effect of temperature on yield in glasshouses in the United Kingdom. The chambers were set at temperatures from 12 °C to 28 °C. There was a strong negative linear relationship between relative yield and temperature ($p < 0.001$, $R^2 = 0.85$). Relative yield decreased by 5.2% for each degree increase in temperature (Table 1).

Table 1. Relationship between relative yield and daily mean temperature in strawberry. Data from the sources shown in the table. CE = controlled environment; s.e. = standard error.

Reference	Type of Exp.	Range in Mean Temp.	Range in Yield (g per plant)	Regression between Yield and Temp.	p Value from Regression	R^2 Value from Regression	Slope from Linear Regression (± s.e.)
Bjurman [27]	Field	13 °C to 17 °C	33 to 315	Linear	0.656	-	-
Kumakura and Shishido [28]	CE	15 °C to 25 °C	26 to 132	Linear	<0.001	0.86	−0.0616 (0.0087)
Le Mière et al. [29]	CE	12 °C to 28 °C	About 31 to 230	Linear	<0.001	0.85	−0.0519 (0.0038)
Kadir et al. [30]	CE	20 °C to 30 °C	3.0 to 9.0	Linear	0.087	0.75	−0.5110 (0.0161)
Wagstaffe and Battey [31]	CE	15 °C to 27 °C	889 to 1497	Linear	0.650	-	-
Krüger et al. [32]	Field	13 °C to 16 °C	112 to 797	Linear	0.723	-	-
Krüger et al. [32]	Field	15 °C to 21 °C	112 to 797	Linear	0.043	0.31	0.1088 (0.0462)
Palencia et al. [33]	Field	9 °C to 15 °C	About 5 to 75	Linear	<0.05	0.86	-
Palencia et al. [33]	Field	9 °C to 15 °C	About 5 to 120	Quadratic	>0.05	-	-
Cocco et al. [34]	Field	12 °C to 14 °C	317 to 1139	Linear	0.001	0.52	−0.2241 (0.0556)
Cocco et al. [34]	Field	11 °C to 14 °C	317 to 1139	Linear	0.006	0.41	−0.1292 (0.0396)
Taghavi et al. [35]	Field	15 °C to 20 °C	67 to 314	Linear	0.532	-	-
Rahman et al. [36]	Field	15 °C to 20 °C	222 to 480	Linear	0.019	0.51	−0.1531 (0.0677)
Rahman et al. [36]	Field	19 °C to 22 °C	250 to 650	Linear	0.101	0.53	−0.1832 (0.0781)
Rahman et al. [36]	Field	20 °C to 23 °C	172 to 414	Linear	0.036	0.75	−0.2264 (0.0626)
Rahman et al. [36]	Field	18 °C to 22 °C	78 to 175	Linear	0.018	0.84	−0.1983 (0.0421)
Condori et al. [37]	Field	-	0 to 80	Linear	<0.001	0.28	-
Condori et al. [37]	Field	-	0 to 80	Linear	<0.001	0.26	-
Condori et al. [37]	Field	-	0 to 80	Linear	<0.001	0.18	-
Condori et al. [37]	Field	-	0 to 80	Linear	<0.001	0.08	-
Sønsteby and Heide [38]	CE	9 °C to 27 °C	0 to 372	Linear	0.586	-	-
Maskey et al. [20]	Field	9 °C to 21 °C	About 3 to 109	Linear	-	0.45	−0.0755
Maskey et al. [20]	Field	8 °C to 24 °C	About 12 to 870	Linear	-	0.27	−0.0939
Butare [39]	CE	20 °C to 30 °C	195 to 1131	Linear	0.248	0.71	−0.0837 (0.0339)
Rivero et al. [40]	CE	9 °C to 27 °C	590 to 1594	Linear	0.077	0.10	−0.0308 (0.0663)
Zhang et al. [41]	CE	8 °C to 17 °C	106 to 871	Linear	0.102	0.71	-

5. Effect of Global Warming on Yields in Queensland

The daily mean temperature has increased by 2 °C at Nambour over the past five decades. There has been a smaller change at Applethorpe, with the daily mean increasing by 1 °C. The analysis detailed above (Table 1; Figure 3) suggests a decrease in yield of 28% on the Sunshine Coast over this period, and a decrease of 14% on the Granite Belt.

6. Interaction between Elevated CO_2 and Temperature on Yield

Increases in temperature with climate change are coupled with increases in the concentration of CO_2 in the atmosphere. The concentration of CO_2 in the lower atmosphere in 2021 was 415 ppm [43]. There is an initial increase in yield with climate change due to higher photosynthesis under elevated CO_2. However, eventually the impacts of high temperatures on growth override the benefits of higher photosynthesis in many species [44–46].

Environmental conditions affect photosynthesis in strawberry leaves. Net CO_2 assimilation increases with increasing concentrations of CO_2 and is saturated with an external concentration of CO_2 (C_a) of 600 to 1,500 ppm [47–49]. The leaves can adapt to elevated CO_2 over the long-term, with the response to higher CO_2 diminishing over weeks or months [50]. Temperature also affects photosynthesis. There is a broad optimum for maximum net CO_2 assimilation, with photosynthesis decreasing only under extreme conditions. The optimum range varies with cultivar and growing conditions and is usually from 20 °C to 30 °C [49–52]. Carlen et al. [53] examined the effect of temperature on CO_2 assimilation in Switzerland. The optimum temperature for photosynthesis was 25 °C to 35 °C, with lower photosynthesis at lower or higher temperatures. Net CO_2 assimilation was adapted to a wide range of conditions and was 60% of maximum values at 40 °C. The optimum temperature range typically increases when the plants are grown at higher temperatures [54].

Several studies have demonstrated that elevated concentrations of CO_2 increase the yield of strawberry compared with ambient conditions [55–60]. This response suggests that higher concentrations of CO_2 under climate change will counteract the impacts of higher temperatures. However, the limited data available indicate that elevated concentrations of CO_2 are not beneficial when combined with elevated temperatures [61,62].

In the study of Balasooriya et al. [61] in Australia, net CO_2 assimilation was higher at concentrations of CO_2 of 650 or 900 ppm than at 400 ppm (Table 2). In contrast, temperature only had a small effect on CO_2 assimilation. Yields were higher at intermediate CO_2 and lower at 30 °C than at 25 °C. The highest yields were obtained at 25 °C with CO_2 levels of 400 or 650 ppm. Sun et al. [62] examined the effect of CO_2 and temperature on the yields of strawberry in growth chambers in China. Control plants under ambient CO_2 (360 ppm) and temperatures (20 °C/15 °C) had similar yields as those under ambient CO_2 and elevated temperatures (25 °C/20 °C) or under elevated CO_2 (720 ppm) and elevated temperatures (10.5 to 12.0 g dry weight per plant; $p > 0.05$). The plants at elevated CO_2 and ambient temperatures had higher yields than the other treatments (25 g dry weight per plant; $p < 0.05$). These results suggest that high CO_2 under climate change is not likely to override the impact of global warming on productivity.

Yuan et al. [63] modelled the changes in productivity of several field crops in Oklahoma, United States. They found that the yields of soybean, sorghum, wheat and canola decreased by 5.7% to 19.2% under climate change. Elevated concentrations of CO_2 increased photosynthesis, but this benefit was dissipated by the impacts of hot and dry weather on growth.

Table 2. The effect of elevated CO_2 and temperature on net CO_2 assimilation and yield of strawberry in glasshouses in Melbourne, Australia. Data are the means (±s.e. or standard error) of two cultivars. Data were retrieved from Balasooriya et al. [61].

Temperature	Concentration of CO_2	Net CO_2 Assimilation (μmol per m^2 per s)	Yield (g per plant)
25 °C	400 ppm	10.3 ± 0.3	46.9 ± 9.3
25 °C	650 ppm	15.1 ± 0.2	52.3 ± 5.1
25 °C	950 ppm	15.0 ± 0.1	39.2 ± 1.5
30 °C	400 ppm	11.1 ± 0.7	8.3 ± 0.9
30 °C	650 ppm	14.2 ± 0.03	35.6 ± 1.6

Table 2. *Cont.*

Temperature	Concentration of CO_2	Net CO_2 Assimilation (μmol per m^2 per s)	Yield (g per plant)
30 °C	950 ppm	12.0 ± 0.1	23.2 ± 4.8
Means			
Temperature (25 °C)		13.5 ± 1.3	46.2 ± 3.1
Temperature (30 °C)		12.4 ± 3.7	22.4 ± 6.5
CO_2 (400 ppm)		10.7 ± 0.3	27.6 ± 13.7
CO_2 (650 ppm)		14.7 ± 0.3	43.9 ± 5.9
CO_2 (950 ppm)		13.5 ± 1.1	31.2 ± 5.7

7. Conclusions

The main scenarios for global climate change include increases in the concentration of carbon dioxide (CO_2) and average temperatures. The daily mean temperature has increased by 2 °C on the Sunshine Coast over the past five decades. The impact of global warming has been less severe on the Granite Belt, with a 1 °C increase in temperature. These increases in temperature are associated with a decrease in yield of 14% to 28% in the two areas. There will be further decreases in yield in the next few decades in the absence of heat-tolerant cultivars or other mitigating strategies.

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Data Availability Statement: The data presented in this study are available on request from the author.

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Conflicts of Interest: The author declares no conflict of interest.

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